A Study on Design Parameters of Stirling Engines for Buildings[1]

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Abstract:One of the most promising projects in the application of combined heat and power(CHP) lies in energy production for buildings. Stirling engines are very applicable to residential buildings, especially because of the higher electricity/heat efficiency. A literature review on stirling engines is first provided and a number of research works on the development and applications of Stirling engines are discussed. Then according to buildings' energy consumption, relevant output of power density of Stirling engines is estimated. From the results, the design parameters of Stirling engines are derived and the temperature difference on frequency and performance of Stirling engines is also discussed.[1]

Key words: Stirling engine; frequency band; buildings

1. INTRODUCTION

Solar energy is one of the more attractive renewable energy sources that can be used as an input energy source for heat engines. Green buildings are a key issue for all over the world. In fact, any heat energy source can be used with the Stirling engine. The solar radiation can be focused onto the displacer hot-end of the Stirling engine, thereby creating a solar-powered prime mover. The direct conversion of solar power into mechanical power reduces both the cost and complexity of the prime mover. In theory, the principal advantages of Stirling engines are their use of an external heat source and their high efficiency. Stirling engines are able to use solar energy that is a cheap source of energy. Since during two-thirds of the day, solar energy is not available, solar/fuel hybrids are needed. For solar electric generation in the range of 1-100Kw, the Stirling engine was considered to be the cheapest[1]. Stirling engines are very applicable to residential buildings, especially because the higher electricity/heat efficiency. Commercially, small-scale fuel cells are in a development phase, whilst a small number of stirling engine units have been deployed on a demonstration basis and developers are preparing to manufacture the product on a larger scale. Electrical efficiency is roughly 15% at the design point, and decreases as power output decreases.

The objective of this article is to provide a basic review of existing literature on Stirling engines and low temperature differential Stirling engine technology. According to buildings' energy consumes, relevant output of power density of Stirling engines is estimated. From the results, the design parameters of Stirling engines is derived and the temperature difference on frequency and performance of Stirling engines is also discussed.

Dish-Stirling systems track the sun and focus solar energy into a cavity receiver where it is absorbed and transferred to a heat engine/generator. Figure 1 is a representation of a Dish Stirling System with the major system components, the dish, the power conversion unit(PCU), etc. identified. Stirling engines are preferred for these systems because of their high efficiencies (thermal-to-mechanical efficiencies in excess of 40% have been reported), high power density (40–70 kW/liter for solar engines),and potential for long-term, low-maintenance operation. Dish-Stirling systems are modular, i.e., each system is a self-contained power generator, allowing their assembly into plants ranging in size from a few kilowatts to tens of megawatts.

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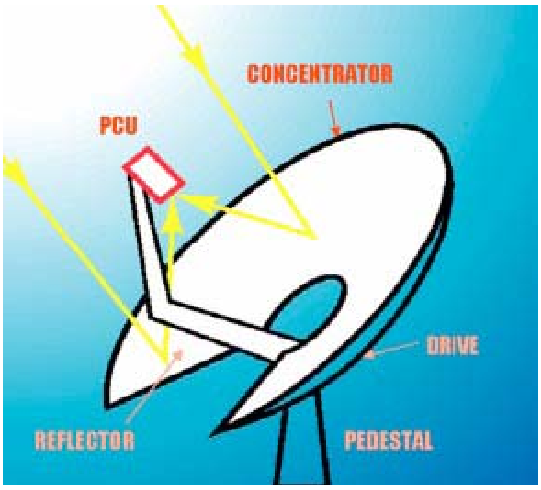

Fig.1 Dish Stirling system components

In 1991, Cummins Power Generation, started development of two Dish-Stirling systems—a 7-kW system for remote applications and a 25-kW system for grid-connected power generation [2,3]. Cummins was innovative in its Dish-Stirling systems, incorporating a lot of advanced technologies into the designs, including a solar concentrator with a polar-axis drive and polymer, stretched-membrane facets, heat-pipe receivers, and free-piston Stirling engines. The heat-pipe receiver transfers the absorbed solar heat to the engine by evaporating sodium and condensing it on the tubes of the engine heater head. The receiver serves as a thermal buffer between the concentrator and the engine, and because it transfers heat to the engine by condensation, it allows the engine to operate at a high average temperature and efficiency [4,5]. Dish-Stirling systems have demonstrated that they are capable of producing electricity for the grid and for remote power applications. Technology development needs are for low-cost components and systems that can operate unattended at very high levels of reliability. Current efforts are focused on establishing reliability and, through break-and-repair approaches, identifying the components that require improvement, redesign, and replacement. In a parallel approach, advanced components, such a heat-pipe receivers, controls, and optical surfaces, that promise higher reliability and lower cost are being designed and tested.

low temperature Stirling engines are not as successful as their high temperature counterparts.S.Abdullah et al[6] proposed a conceptual design of low temperature differential double-acting Stirling engine for solar application.K.Bancha and W. Somchai[7] proposed a review of solar-powered Stirling engines and low temperature differential Stiling engines.

2. CONCEPTUAL DESIGN AND POWER CALCULATION OF STIRLING ENGINE FOR BUILDINGS

2.1 Conceptual Design

Schematic diagram of a gamma-configuration Stirling engine are shown in Fig. 2. According to the mechanical configurations of Stirling engines, which are classified into the alpha-, beta-, and gamma-configuration, slight differences in their p–v diagrams result in the cycle net works not being the same. The Schmidt or West formula can be used to make a calculation of engine shaft power.

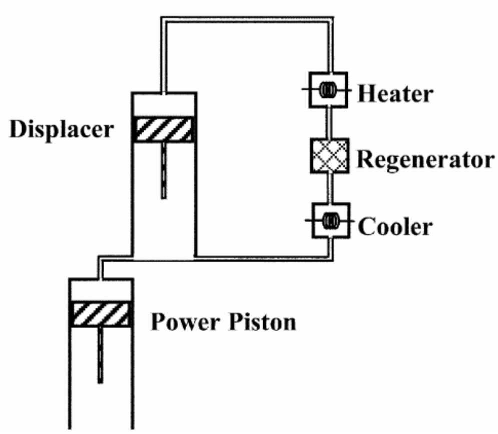

Fig.2 Schematic diagram of a gamma configuration Stirling engine

The Stirling engine need a complete design analysis,it can be subdivided into four stages: the analysis of swept volumes and dead volumes; the analysis of heater and cooler parameters; the analysis of regenerators; and, finally, the optimisation the critical engine parameters.

2.2 Power Calculation of Stirling Engine

Schmidt [8] showed a mathematically exact expression for determining the indicated work per cycle of a Stirling engine. The Schmidt formula may be shown in various forms depending on the notations used. Because of its complexity, it takes time to verify the calculation [9]. The calculation for gamma configuration Stirling engines is as follows [10]:

$$W = \pi(1-\tau) p_{\max} V_D \frac{k_P \sin\alpha}{Y+\sqrt{Y^2-X^2}} \sqrt{\frac{Y-X}{Y+X}} \quad (1)$$

Where $k_P = V_P / V_D$ $V_D = A_D L_D$ $V_P = A_P L_P$

$$X = \sqrt{(1-\tau)^2 - 2(1-\tau)k_P \cos\alpha + k_P^2}$$

$$Y = 1+\tau+\frac{4k_s\tau}{1+\tau}+k_P \quad \tau = \frac{T_C}{T_H} \quad k_s = \frac{V_s}{V_D}$$

Where W is the indicated work per cycle in N m, $p_{\max}$ the maximum pressure attained during cycle in N/m^2, k_P the swept volume ratio, k_s the dead space volume ratio, V_D the displacer swept volume in m^3, V_P the power piston swept volume in m3, V_S the dead space volume in m^3, A_D the displacer cylinder cross-section area in m^2, A_P the power cylinder cross-section area in m^2, L_D the displacer stroke in m, L_P the power piston stroke in m, a the phase angle lead of the displacer over the power piston in degrees, and t is the temperature ratio.

Because it is more convenient to use the mean or average cycle pressure, p_m, instead of the maximum cycle pressure, $p_{\max}$, the maximum pressure under the Schmidt assumptions is related to the average cycle pressure [9]. It is as follows:

$$p_{\max} = p_m \sqrt{\frac{Y+X}{Y-X}} \quad (2)$$

Substituting Eq. (2) into Eq. (1) gives the simpler form of the Schmidt formula for determining the indicated cyclic work of the gamma-configuration Stirling engine:

$$W = \pi(1-\tau) p_m V_D \frac{k_P \sin\alpha}{Y+\sqrt{Y^2-X^2}} \quad (3)$$

West [9] proposed a simpler formula to determine indicated work as follows:

$$W = \frac{\pi p_m}{2} \frac{V_D V_P}{V_D + 0.5V_P + V_s} \frac{T_H - T_C}{T_H + T_C} \sin\alpha \quad (4)$$

Eq. (4) gives an error of the indicated work for sinusoidal motion compared to the exact solution from Eq. (16). However, it is more popular because of its simplicity.

Beale [11] noted that the power output of several Stirling engines observed could be calculated approximately from the equation:

$$P = 0.015 p_m f V_P \quad (5)$$

where P is the engine power output in Watts, p_m the mean cycle pressure in bar, f the cycle frequency in Hz, and V_P is displacement of power piston in cm^3. The Beale formula can be used for all configurations and for various sizes of Stirling engines. Eq. (4) may be written in a general form as follows:

$$P/(p_m f V_P) = cons\tan t \quad (6)$$

The resulting dimensionless parameter $P/(p_m f V_P)$ is called the Beale number. It is clear that the Beale number is a function of both source and sink temperatures. The solid line in Fig. 6 indicates the relationship between the Beale number and source temperature. The upper bound represents the high efficiency, well-designed engines with low sink temperatures, while the lower bound represents the moderate efficiency, less well-designed engines with high sink temperatures [12]. The Beale number correlation was modified by Walker [13], West [14], This correlation is used to determine the Stirling engine shaft power output as follows:

$$P = F p_m f V_P \frac{T_H - T_C}{T_H + T_C} \quad (7)$$

Eq. (7) is a powerful tool in the first step of the design. Senft [9] and West [14] described that an F value of 0.25–0.35 may be used for practical use.

The pressure ratio and heat transfer of the heater and cooler are showed as follows[10]:

$$\gamma = p_{\max} / p_{\min} = (1+\delta)/(1-\delta) \quad (8)$$

$$Q_E = \frac{1}{2}\pi p_m V_E \Delta \sin\theta_1 = \frac{\pi p_m V_E \delta \sin\theta_1}{1+\sqrt{1-\delta^2}} \quad (9)$$

$$Q_C = \frac{\pi p_m V_E \kappa \delta \sin(\theta_1 - \alpha)}{1 + \sqrt{1-\delta^2}} \tag{10}$$

Where $\delta = A_1 / B_1$

$$A_1 = (\tau^2 + 2\tau\kappa\cos\alpha + \kappa^2)^{1/2}$$

$$B_1 = \tau + \kappa + 2s$$

2.3 The Frequency Band Under Different Power Density of Buildings

F Meillaud[15] gave a evaluation of a building 232MJ/y,,Usually buildings have 200-20000m^2 then,the requirement of energy is 1.47KW~147KW.From Eq.(5),it is showed that the frequency band under different density of buildings as Fig.3:

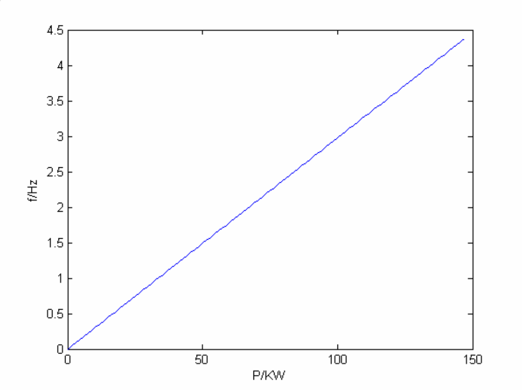

Fig.3 Relationship between power and working frequency

3.RESULTS AND DISCUSSION

It is obvious from Schmidt-cycle equations that the net cycle power and the thermal load on the heat exchangers are direct linear functions of the engine speed (N), the maximum pressure of the working fluid ($p_{\max}$) and the size of the engine, which is expressed in term of the swept volume . However, the direct effects of the dead volume and swept volume to the engine power should be detailed. Fig. 4 illustrates the variation of the power as a function of the swept volume, which was calculated on the dead volumes of 2500 and 5000cm^3 under the fixed temperature difference of 50 . It is shown that the power increases when the swept volume increases. Also, it is noticeable that the speed increases with the increase in power. These two remarks imply that the swept volume is proportional to the engine power for several speeds. The variation of the engine power as a function of dead volume is calculated and the results are shown in Fig.5 for the engine speed of 100 rpm. It is shown that the power decreases when the dead volume increases and decreases with the decrease in s wept volume.

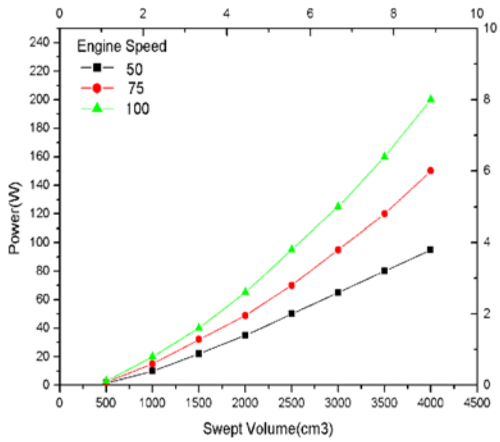

Fig.4 Influence of swept volume on engine power(Dead volume of 2500cm^3)

Tab.1 optimization of frequency band

	SAIC/STM System	SBP System	SES System	WAG(Mod1) ADDA System	WAG(Mod2) Remote System
Aperture Dia.(cm)	38	15	20	14	14
No. of Cylinders	4	2	4	2	2
Displacement(cc)	480	160	380	160	160
Operate Speed(rpm)	2200	1500	1800	1800	800-1890
Working Fluid	hydrogen	helium	hydrogen	hydrogen	hydrogen
Ann Efficiency Net	14.50%	15.70%	24.60%	18.90%	18%

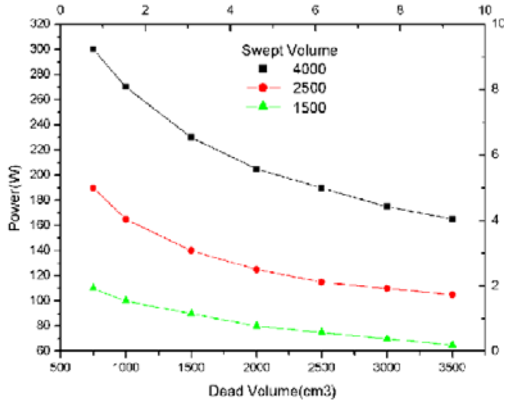

Fig.5 Influence of dead volume on engine power(Engine speed of 100 rpm).

Influence of some other parameters on Stirling engine is showed as Fig.6.

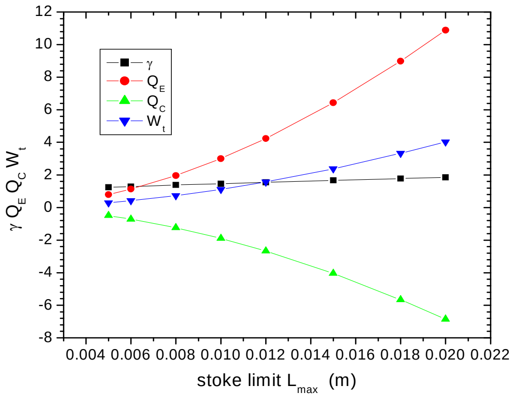

Fig.6 Influence of stroke of piston on pressure ratio γ ,expansion heat Q_E ,compression heat Q_C and cycle outpower W

It is seen that the stroke of piston has a significant influence on the heat transfer of expansion space and compression space , a optimized stroke of piston and corresponding swept volume and dead volume are needed.

4 CONCLUSION

In this paper, a number of technical parameters in designing a Stirling engine have been proposed. These relationships of some parameters have been established through the use of the Schmidt analysis and have later been optimised.The study can provide a basis of a novel energy production for buildings by applying Stirling engines.

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